Comparative Assessment of Post-Combustion and Pre-Combustion Carbon Capture Technologies

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Abstract. With the growing concern over carbon dioxide emissions in recent years, carbon capture and storage (CCS) technology, as a highly promising method for mitigating climate change, has received increasing attention, and related research has also been on the rise. This review focuses on a comparative analysis between pre-combustion and post-combustion carbon capture technologies, concerning aspects such as economic costs, carbon dioxide capture efficiency, and deployment applicability. The review first outlines the basic processes involved in the two technologies and compares their operational mechanisms and associated technologies. Then, based on a standardized case study of a 230 MW coal-fired power plant, a further detailed comparison was carried out through simulation and cost analysis to evaluate CO_2 capture efficiency, total captured volume, and related costs. The analysis shows that while post-combustion offers slightly higher capture efficiency, pre-combustion has significant advantages in energy conservation and cost-effectiveness under high-pressure conditions. Moreover, post-combustion systems are better suited for retrofitting existing power plants because of their simpler design, whereas pre-combustion systems are more appropriate for new installations. The review concludes that both of these carbon capture technologies are viable, mainly depending on specific project requirements and infrastructure environment. This review provides a certain reference value for policymakers and engineers on how to select the suitable carbon capture technology, and highlights the significance of integrating technical, economic, and environmental factors during the deployment of CCS technology.

Keywords: carbon emission, carbon capture and storage, sustainable energy engineering, climate change mitigation technologies

1. Introduction

With the accelerated development of urbanization and industrialization, carbon dioxide emissions have increased relative to the standard carbon cycle system [1]. In 2024, global coal-fired power generation rose to a record high of 10,700 TWh, driven by persistent demand in the electricity sector, which still accounts for two-thirds of global coal consumption [2]. Despite the growth of renewables, fossil fuel-based power plants continue to be the dominant source of CO_2 emissions [3]. These emissions drive global warming and environmental degradation, posing a significant danger to the global ecological balance. Therefore, it is crucial to take mitigation measures to reduce the

threat of CO_2 to humanity and the ecosystem. Based on this global situation, carbon capture and storage (CCS) technology has become a promising method to effectively reduce carbon dioxide emissions while utilizing fossil fuels for power generation [4]. This involves capturing emissions from power plants before CO_2 is released into the atmosphere.

Pre-combustion capture, a core carbon capture technology, converts fuel into syngas before combustion and extracts CO_2 from this stream, enabling carbon capture before power generation [5]. Conversely, post-combustion capture separates CO_2 from flue gas after combustion [6]. Both technologies present distinct advantages and challenges in efficiency, cost, energy penalty, and technical feasibility.

Employing a systematic analysis of the literature, this review comprehensively compares the technical performance and economic-environmental dimensions of pre-combustion and post-combustion carbon capture technologies, providing evidence-based decision support for selecting and optimizing carbon reduction strategies.

2. Technical principles and process comparison

This section introduces three principal post-combustion carbon capture methods: chemical/physical absorption, adsorption, and membrane separation. Concurrently, it examines three physical solvent-based pre-combustion technologies: Selexol (dimethyl ether-glycol mixture for dual-stage H_2S/CO_2 removal), Purisol (N-methyl-2-pyrrolidone solvent with integrated Claus sulfur recovery), and Morphysorb (N-formylmorpholine achieving >99% sulfur yield).

2.1. Post-combustion technology

Post-combustion carbon dioxide capture methods primarily remove CO_2 and other gaseous pollutants from fossil fuel combustion through physical or chemical processes [6]. Depending on the underlying separation mechanism, the key method includes adsorption, absorption, and membrane separation. As illustrated in Figure 1, several important steps are involved in the operation of a temperature swing CO_2 capture setup employing solid sorbents, such as adsorption, desorption, and gas separation units. This figure highlights the cyclic operation between the adsorption and regeneration phases, which ensures the efficiency of the absorbent and the stability of the system.

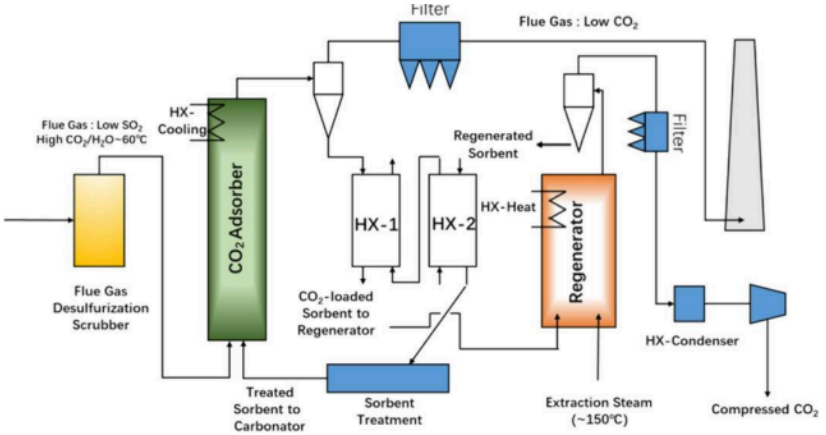

Figure 1. Flowsheet of a temperature swing CO_2 capture using solid sorbents [7]

2.1.1. Adsorption method

In the post-combustion adsorption process, CO_2 can be captured through either physisorption or chemisorption. Physisorption relies on weak van der Waals forces and typically uses materials like activated carbon and zeolites [8]. In contrast, chemisorption involves the formation of chemical bonds, often utilizing amine-functionalized solid sorbents [6]. When the adsorbent reaches the saturated state, the CO_2 is released by pressure swing adsorption (PSA), temperature swing adsorption (TSA), vacuum swing adsorption (VSA), and other methods, so as to realize the regeneration of the adsorbent.

In the PSA, as CO_2 is adsorbed onto the surface of a solid adsorbent under high pressure and then released under low-pressure [7]. Figure 2 illustrates the basic process flow of PSA, where gas separation is achieved through cyclic pressure changes in packed adsorption beds. Under high-pressure conditions, CO_2 binds more strongly to the adsorbent compared to N_2. After saturation, the system undergoes regeneration by lowering the pressure, enabling the desorption and recovery of CO_2. This process is based on the different molecular properties and affinities of CO_2 and N_2 for solid adsorbents.

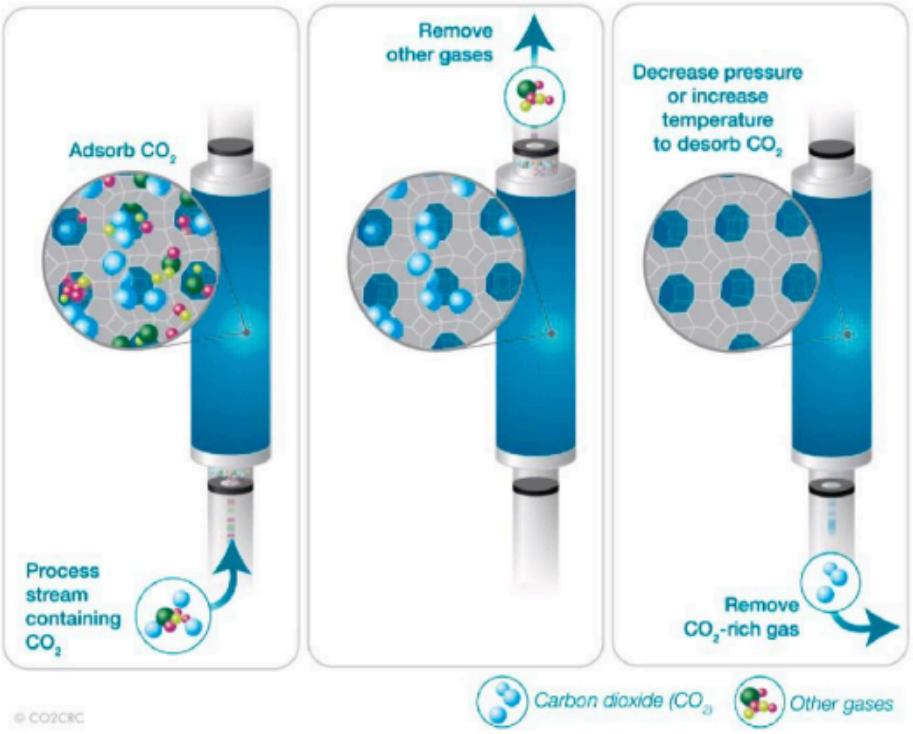

Figure 2. The adsorption used in post-combustion technology [7]

The TSA process mainly involves adjusting the operating temperature to achieve CO_2 adsorption and desorption, which will be periodically alternated, adsorption process is mainly carried out at a lower temperature, and desorption requires heating the adsorption bed [7]. TSA has only a little impact on the magazine in the flue gas. Such as H_2S and water vapour can be removed when the temperature is ~ 160°C [7]. Also, this method can operate at low pressure and is easy to maintain.

VSA is adsorption at atmospheric pressure followed by desorption under vacuum conditions, and high separation efficiency and yield can be achieved due to high desorption efficiency [7].

The three methods differ in their operating conditions and suitability for various applications. PSA is favored for high-pressure streams due to lower energy penalties associated with pressure swing compared to thermal regeneration in TSA. VSA offers advantages for low-pressure feeds but requires efficient vacuum systems.

2.1.2. Absorption method

The absorption process uses physical or chemical principles to transfer CO_2 from the air stream to a large amount of liquid solvent to achieve capture [7]. As shown in Figure 3, the solvent rich in CO_2 is fed into the thermal degasser for regeneration. In the regeneration process, the absorbed CO_2 is stripped from the solvent, and the solvent is returned to the absorber, so that recycling is achieved.

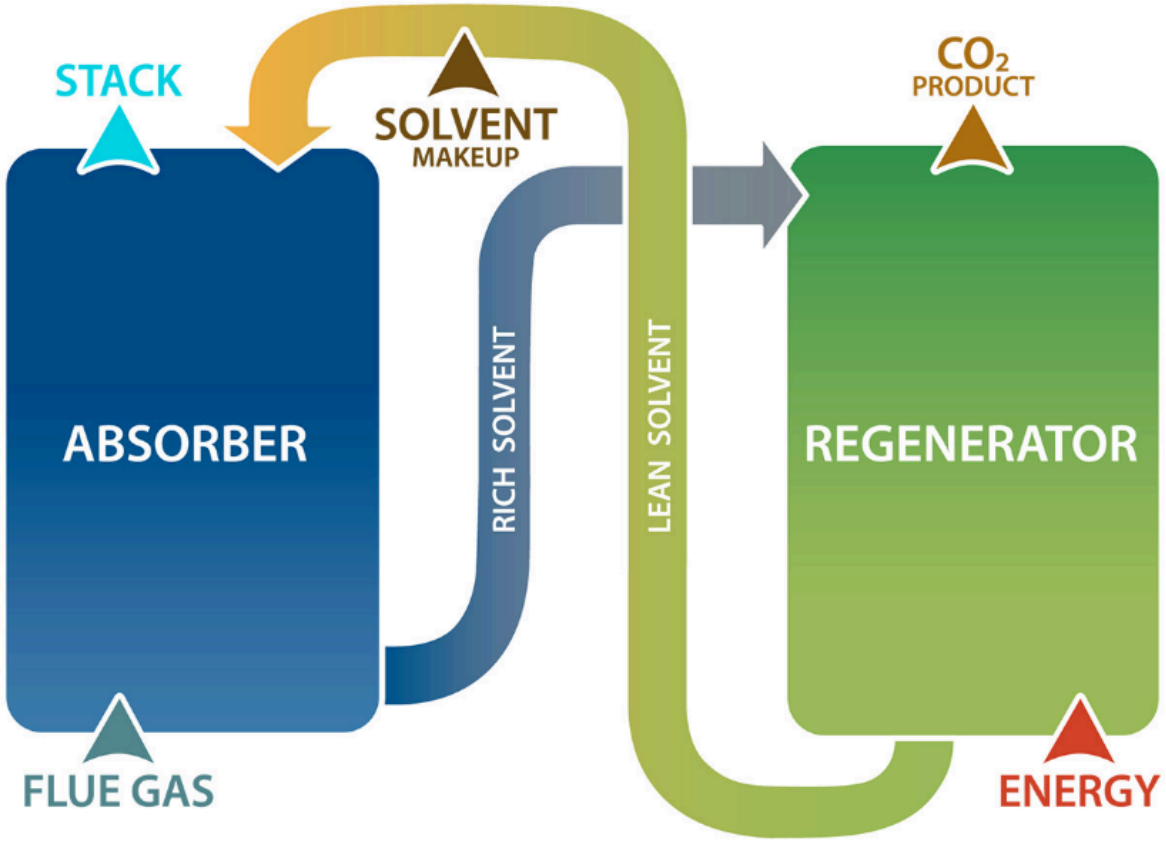

Figure 3. The absorption using in post-combustion technology [9]

Among chemical solvents used in post-combustion CO_2 capture, monoethanolamine (MEA) is still considered the most commonly applied due to its high reactivity with CO_2, with a typical concentration of 30% in aqueous solution. Its high reactivity with CO_2 makes it an effective choice [6]. However, it also presents several operational challenges, including high energy consumption for regeneration, such as MEA-based systems, which may lead to an energy efficiency loss of 25–28% for new power plants and 36–42% for retrofit applications [6]. Also leading to solvent degradation and corrosion of equipment.

2.1.3. Membrane separation method

Figure 4 presents that membrane-based CO_2 separation operates by selectively allowing certain gas molecules to permeate through a semi-permeable membrane while blocking others, based on mechanisms like diffusion, adsorption, molecular sieving, and ionic transport [7]. Two main types of systems are employed: membrane gas separation and membrane contactors, the latter system combining membrane interfaces with absorption. Membrane gas separation relies on pressure gradients to separate CO_2 without solvents and is suitable for high-pressure gas streams [1]. While for membrane contactors, it offers high selectivity and does not require regeneration steps. Due to their solvent-free operation and lack of regeneration requirements, membrane systems provide a cost-effective and operationally simple option for CO_2 separation.

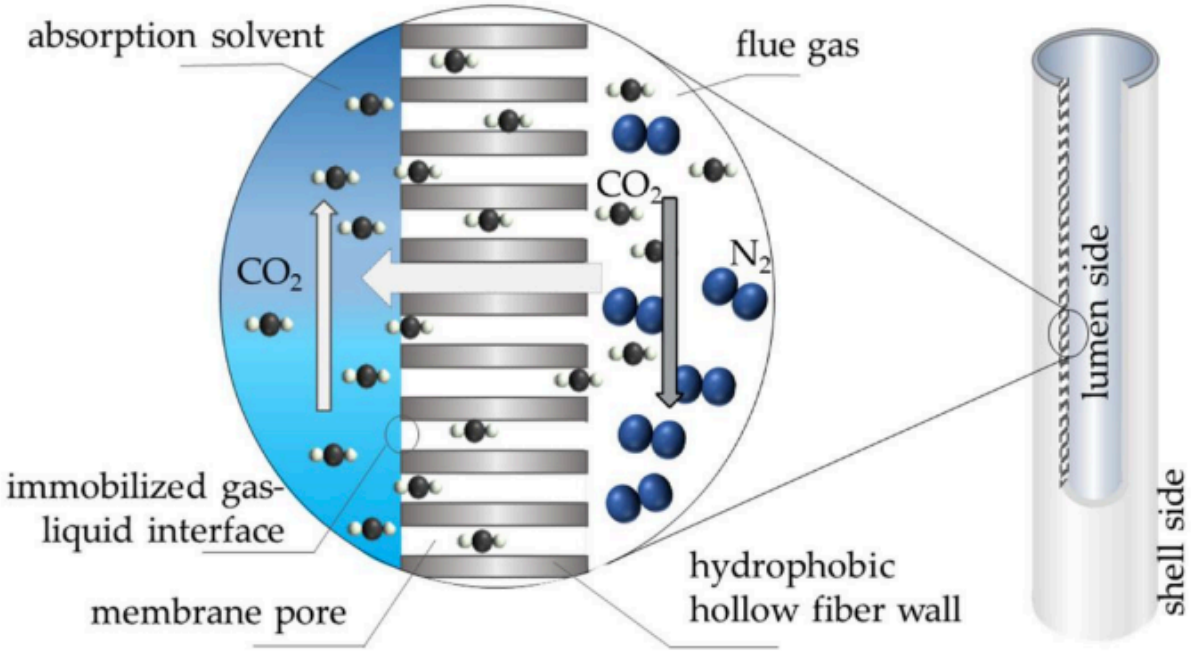

Figure 4. The membrane separation using in post-combustion technology [10]

2.1.4. Integrated comparative analysis and applicability

Among the post-combustion technologies, adsorption, absorption, and membrane separation each offer unique technical and economic profiles. Adsorption technology has low regenerative energy and is easy to operate, which makes it suitable for small and medium-scale systems [6]. Absorption, particularly using aqueous piperazine (PZ), is achieved with high efficiency and perfect performance. So this technology is the most mature and cost-effective choice in large-scale renovations. For membrane separation, although the maturity of this method is still relatively low, it offers potential for the improvement of membrane materials and process designs.

Table 1. Comparative overview of post-combustion CO_2 capture technologies

Comparison Aspect	Adsorption	Absorption	Membrane Separation
Principle	Physisorption/ chemisorption on solid sorbents	Gas-liquid absorption with chemical or physical solvents (e.g. MEA)	Selective gas permeation through semi-permeable membranes
Operating Conditions	Highpressure (PSA), low-pressure + heating (TSA), vacuum desorption (VSA)	Typically low–medium pressure, elevated temperature for stripping	High-pressure for gas-phase modules; moderate pressure for membrane contactors
Key Advantages	Flexible cycles; PSA energy penalty lower than TSA; TSA can remove H_2S / H_2O at ~160 °C; VSA efficient for low-pressure feeds	High reactivity and industrial maturity; continuous solvent recycling	Simple system; no chemicals or solvent regeneration; moderate capital cost; contactors give high selectivity
Key Limitations	Requires swing equipment; VSA needs efficient vacuum; TSA needs heating	High energy consumption; solvent degradation; corrosion	Membrane gas separation needs gas compression

As shown in Table 1, each post-combustion CO_2 capture technology presents distinct operational profiles. For adsorption, it allows cycle flexibility through PSA, TSA, and VSA. While absorption achieves high removal efficiency using solvents like MEA but incurs significant energy and material costs. And for membrane separation, it offers a simpler, solvent-free system, though often constrained by pressure requirements and membrane performance trade-offs.

2.2. Pre-combustion technology

Precombustion is the process of gasifying the fuel before it is burned [11], as shown in Figure 5, which generates syngas primarily composed of H_2 and CO, and then enters the gas separation process to remove CO_2 [5]. One of the most widely used methods for CO_2 separation in this stage is physical solvent-based absorption, especially under high-pressure conditions. Among the processes, the Selexol, Purisol, and Morphysorb processes are the most representative.

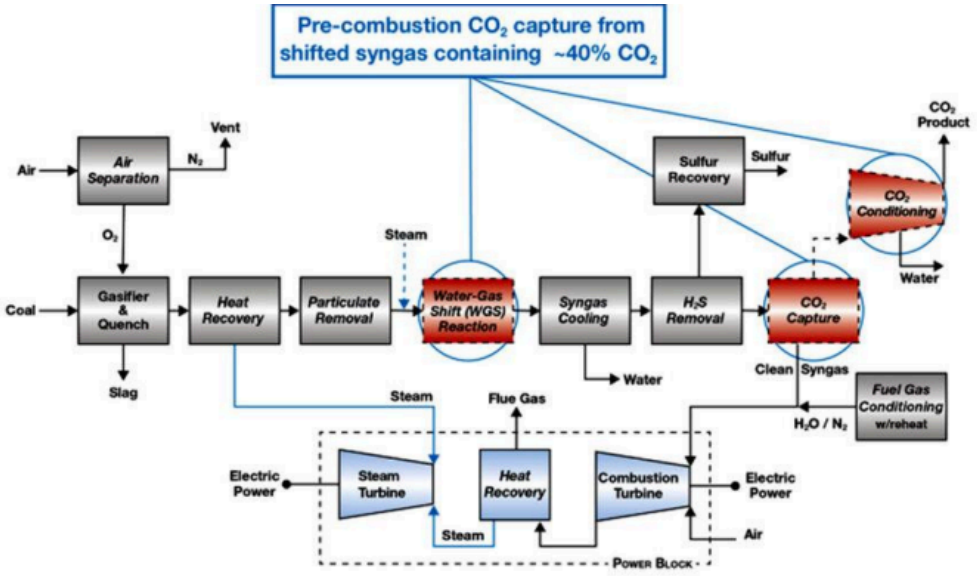

Figure 5. Pre-combustion technology [5]

2.2.1. Selexol process

Selexol is a widely used physical solvent process, it is suitable for high-pressure syngas and can selectively remove CO_2 and sulfur compounds through a two-stage absorption configuration. The Selexol process is a solvent that uses a mixture of dimethyl ether with propylene glycol as an absorber to selectively capture hydrogen sulfide and carbon dioxide from synthetic gases [5]. A two-stage process is usually used, based on Figure 6, it can be observed that this two-stage process involves removing hydrogen sulfide in the first stage and carbon dioxide in the second stage.

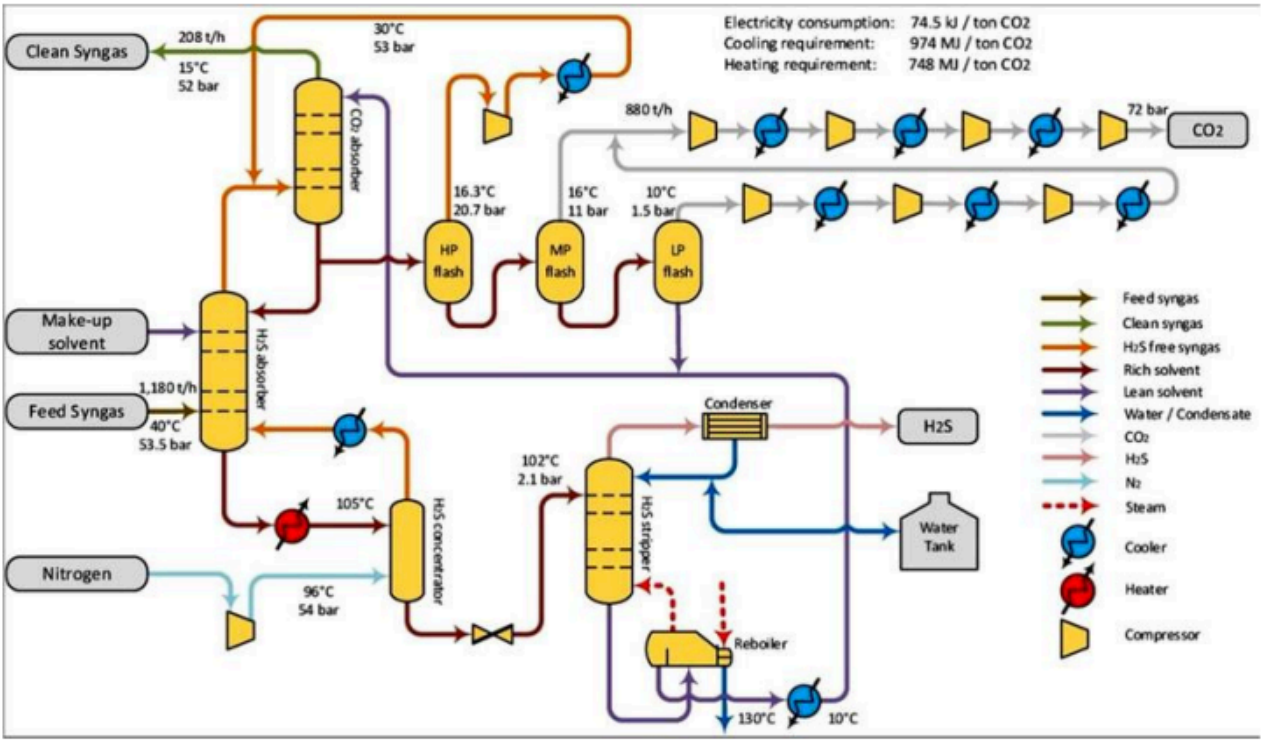

Figure 6. Selexol process [5]

At the beginning of the Selexol process, high-pressure syngas enters the H_2S absorber at around 40°C. In this unit, about 20% of the solvent is recycled from the CO_2 absorber. The main job of the H_2S absorber is to remove hydrogen sulfide from the syngas. Once the solvent becomes saturated, it is heated to about 100°C and sent to the H_2S concentrator [5]. In there, nitrogen gas is added to help separate any CO_2 that was also absorbed. The CO_2 goes back to the H_2S absorber, while the concentrated H_2S is removed from the system. After that, the syngas, which has had most of the H_2S removed, enters the CO_2 absorber, where carbon dioxide is separated. A clean syngas stream was produced after the entire process was completed, which is suitable for power generation or industrial use.

2.2.2. Purisol process

Purisol uses N-methyl-2-pyrrolidone (NMP) as the solvent, due to its excellent H_2S solubility and resistance to sulfur deposition [5], it is particularly effective in handling gas streams with high sulfur content. It can be seen from Figure 7 that at the beginning of the Purisol process, raw gas containing CO_2 and H_2S enters the H_2S absorber, where part of these acid gases are initially removed. The solvent is then depressurized and sent through a reabsorber, which selectively removes any

remaining H_2S before the solvent is recycled back into the main gas stream. Next, a reboiled stripping column is used to completely remove the remaining acid gases from the solvent. The gas exiting the Hot Flash unit which is now mostly purified and sent to an oxygen-blown Claus unit. This unit processes sulfur compounds and produces a tail gas containing H_2, CO, water vapor, CO_2, and any leftover H_2S and SO_2. In the final step, the tail gas undergoes hydrogenation, where residual sulfur compounds are transformed into H_2S. This is followed by a cooling stage to eliminate moisture and any remaining CO_2, thus completing the gas purification process [5].

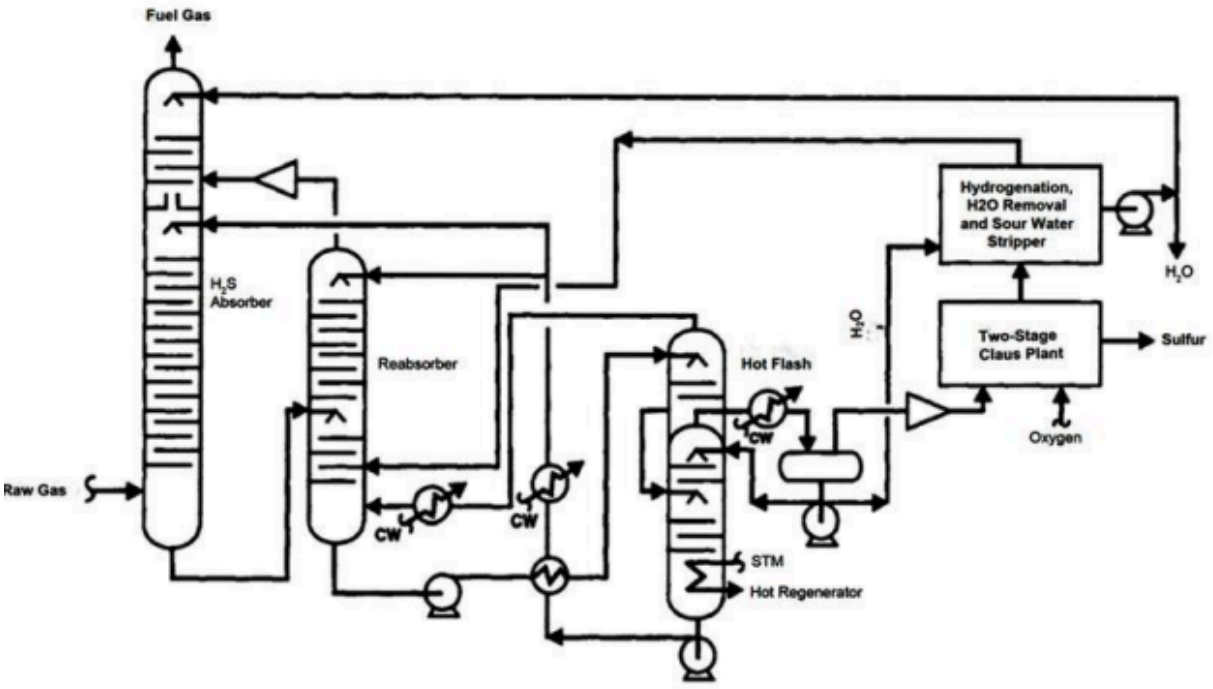

Figure 7. Purisol process [5]

2.2.3. Morphysorb process

Morphysorb is typically applied in Integrated Gasification Combined Cycle (IGCC) and gasification plants. In the Morphysorb process, N-formylmorpholine along with related morpholine compounds is commonly applied for removing CO_2 and H_2S from natural gas and industrial gas streams. In this process, gas containing CO_2 and H_2S first enters two absorbers where these acid gases are captured by the Morphysorb solvent. According to Figure 8, the solvent is then sent through a series of Recycle Flash Drums for regeneration. In the first and second Recycle Flash Drums, the solvent undergoes pressure reduction, then releases light gases. These flash gases are compressed and recycled back into the absorber feed to prevent methane losses. For the third and fourth Recycle Flash Drums, acid gases like CO_2 and H_2S are released. These gases are then compressed and liquefied for injection into underground storage. At the end of the process, the regenerated Morphysorb solvent is returned to the absorbers to complete the cycle [5].

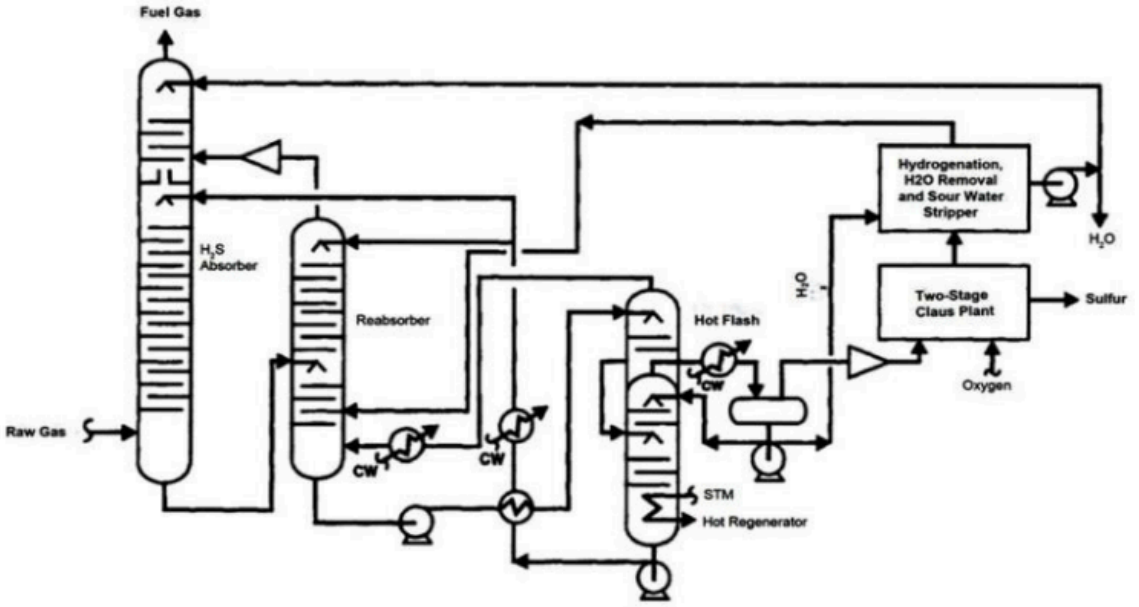

Figure 8. Morphysorb process [5]

2.2.4. Integrated comparative analysis and applicability

Although Selexol, Purisol, and Morphysorb all remove CO_2 and H_2S with physical solvents, they still have differences in aspects, such as solvent chemistry, loop configuration, and sulphur-handling strategy. Selexol emphasises a clean split between H_2S and CO_2, Purisol integrates Claus or hydrogenation for sulphur recovery, while Morphysorb minimises methane loss and achieves very high elemental-sulphur yields, which guides solvent selection toward the most compatible plant layout and product-handling requirement. Table 2 summarizes key differences among the three processes based on solvent type, absorber arrangement, and sulphur-handling approach. As described, Selexol employs a dual-stage absorber for separate H_2S and CO_2 removal, while Purisol integrates a re-absorber to enhance sulphur recovery. Morphysorb, however, utilizes a simplified single-stage absorber design; its high sulphur removal efficiency is achieved through downstream regeneration and disposal options.

Table 2. Process-level comparison of pre-combustion physical solvent systems

Aspect	Selexol	Purisol	Morphysorb
Solvent	Dimethyl-ether / propylene-glycol mixture	N-methyl-2-pyrrolidone (NMP)	N-methyl-2-pyrrolidone (NMP)
Absorber Arrangement	H_2S absorber → CO_2 absorber (dual-stage)	H_2S absorber → re-absorber → stripper	Single-stage absorber with downstream regeneration (Stripper system)
Sulphur Disposition	H_2S concentrated and removed separately	Claus unit + tail-gas hydrogenation	Elemental-sulphur recovery or down-hole disposal

3. Comprehensive performance evaluation

This section presents a comparative evaluation of pre-combustion and post-combustion carbon capture technologies based on the case study by Kheirinik et al.. The study employed Aspen

Hyprotech Systems (HYSYS) simulations for a 230MW coal-fired power plant to ensure consistent boundary conditions for all capture systems. Anthracite was selected as the fuel in all scenarios to ensure comparability. Characterized by a high fixed carbon content (50-98%) and negligible sulfur concentration, anthracite eliminated the need for sulfur treatment units, thereby ensuring clean simulation inputs.

The Taylor cost scoring method was applied to estimate capital costs, offering approximately 95% confidence with an error range of +36% to −26%. This method accounts for throughput, reaction time, and process complexity, making it suitable for preliminary techno-economic assessments [12].

To assess the performance and practicality of the two technologies, three key aspects are evaluated: comprehensive performance, CO_2 capture efficiency, and deployment suitability.

3.1. Techno-economic comparison

According to the U.S. Department of Energy (DOE), the current cost of CO_2 capture using pre-combustion technologies is approximately USD 60 per tonne. The DOE aims to reduce this cost to USD 30 per tonne through research on advanced solvents, adsorbents, and membranes, indicating strong long-term economic potential [13]. Within the case study, pre-combustion capture costs were £60.4 (equivalent to ~USD 77) per tonne of CO_2, significantly lower than the £124.7 (equivalent to ~USD 160) per tonne associated with post-combustion. Both approaches required similar capital expenditures (approximately £240 million). However, the pre-combustion system captures more CO_2 annually (561,954 tonnes versus 485,392 tonnes). This cost advantage is mainly due to the lower energy demand when the pre-combustion capture technology uses high-pressure physical solvents in the process [12].

3.2. Capture efficiency

To ensure meaningful comparison, all systems were modeled to produce the same net output of 230MW, eliminating variability from power generation. Such standardization ensures that observed efficiency differences are primarily attributable to the inherent characteristics of each capture process, minimizing the influence of external operational factors.

Under standardized simulation conditions, both technologies demonstrated high carbon capture efficiency. Post-combustion achieved a capture rate of 92%, slightly higher than the 90% for pre-combustion [12]. This marginal difference may be attributed to the maturity of the commonly used chemical solvent system in post-combustion.

For pre-combustion, the initial simulation used a single water-gas shift (WGS) reactor to increase hydrogen and CO_2 production, but this configuration led to unsatisfactory results and lower CO_2 capture efficiency. Then a second WGS reactor was added, which successfully increased the CO_2 concentration in the shifted syngas, and the overall capture efficiency reached 90% [12]. This outcome illustrates that the efficiency of pre-combustion capture is highly dependent on reactor design and configuration.

3.3. Deployment suitability

The case study highlights significant differences in deployment feasibility between the two systems. Post-combustion technology demonstrates greater flexibility, particularly for retrofitting existing coal-fired power plants. Since the system is installed downstream of the combustion chamber and

directly processes flue gas, it requires fewer structural changes and can be integrated without altering core plant operations.

In contrast, the pre-combustion system is more complex, requiring more process units and steps. Pre-combustion systems require extensive redesign, including gasifiers, dual water-gas shift reactors, and high-pressure CO_2 separation units. These units are typically only feasible in new-build configurations, such as power plants adopting IGCC (integrated gasification combined cycle) technology, where the system architecture can be optimized from the design stage [12]. Although it offers advantages in CO_2 concentration and energy use, it also involves higher construction costs and engineering demands, making it less suitable for retrofitting existing plants.

3.4. Integrated comparison of carbon capture technologies

Integrating techno-economic metrics (e.g., £77 vs £160/tCO_2 capture cost), efficiency profiles (90% vs 92% recovery), and deployment constraints (greenfield-only vs retrofit flexibility), Table 3 systematically quantifies critical distinctions between pre-combustion and post-combustion technologies. This enables evidence-based trade-off analysis for power projects, prioritizing cost efficiency in new IGCC builds versus retrofit feasibility in legacy coal fleets.

Table 3. Comprehensive comparison of two combustion technologies

Evaluation Dimensions	Pre-combustion	Post-combustion
Capture Cost (USD/tCO_2)	77	160
Energy Profile	HP solvents, Low energy	Chemical solvents, High energy
Capture Efficiency	90%	92%
System Complexity	High	Low
Applicable Scenario	Greenfield plants (IGCC)	Retrofit for existing plants
Technical Constraint	Reactor configuration dependency	Solvent maturity dependency

3.5. Innovation pathways for carbon capture technologies

Beyond current techno-economic assessments, emerging innovations promise to address key limitations of both capture technologies. One highly promising future innovation lies in the improvement of membrane materials, particularly the development of mixed-matrix membranes (MMMs) incorporating fillers such as metal-organic frameworks (MOFs) or carbon molecular sieves (CMSs). These advances enhance CO_2 selectivity and permeability while maintaining the environmental and operational advantages of membrane systems [14]. This enables it to further demonstrate its advantages in post-combustion CO_2 capture. Another transformative optimization approach leverages Artificial Intelligence (AI) for real-time control to minimize regeneration energy consumption. Through real-time monitoring and control of crucial operational factors—such as temperature, flow rate, and solvent regeneration rate—in systems like amine scrubbing, AI algorithms can dynamically adjust regeneration cycles, thereby significantly lowering reboiler duty [15]. Current cutting-edge research focuses on integrating AI with digital twin technologies to create adaptive, self-optimizing carbon capture operations.

4. Conclusion and outlook

4.1. Conclusion

This review elucidates critical trade-offs in deploying carbon capture technologies for coal-fired power generation. Pre-combustion capture emerges as the economically superior option for new-build IGCC plants, with a capture cost of £60.4/tCO_2 (£77/tCO_2)—less than half the £124.7/tCO_2 (£160/tCO_2) required for post-combustion systems, primarily due to reduced energy penalties under high-pressure conditions. Both technologies achieve robust capture efficiencies (90% for pre-combustion vs. 92% for post-combustion), yet their limitations are distinct: pre-combustion efficiency is highly sensitive to reactor design (e.g., dual WGS configurations), while post-combustion faces solvent degradation issues that increase operational costs. Notably, the retrofit flexibility of post-combustion systems—enabled by downstream integration with existing flue gas streams—contrasts sharply with the greenfield-only feasibility of pre-combustion, which demands gasifiers and specialized separation units. These findings underscore that technology selection must align with plant-specific conditions, balancing upfront costs against long-term operational stability.

4.2. Outlook

While this review provides a comprehensive analysis of the techno-economic trade-offs inherent in standalone carbon capture systems and offers a valuable comparison of diverse capture technologies, it is crucial to recognize that the effective deployment and success of CCS as a climate solution fundamentally depend on the synergistic optimization of the entire integrated value chain. Consequently, future research endeavors must urgently prioritize extending their scope significantly beyond the singular focus on capture alone. This expanded focus should explicitly encompass and rigorously investigate the complete CCS chain in its entirety. A deeper, more holistic investigation into these broader, systemic, and interconnected aspects is absolutely essential and imperative. Only through such comprehensive research can we establish the robust scientific foundation and generate the necessary, actionable decision-support tools critically required to enable and accelerate the large-scale commercial deployment of CCS technology.

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